A SMART TWO-CELL RANDOM ACCESS ALGORITHM FOR WIRELESS CDMA COMMUNICATION NETWORKS USING SMART ANTENNA

By

Enfel Barkat

B.S., American University of Sharjah, 2010

A thesis submitted to

the Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Master of Science

Electrical Engineering

2013

The thesis for the Master of Science degree

by

Enfel Barkat

has been approved for the

Electrical Engineering Program

By

Titsa Papantoni, chair

Jan Bialasiewicz

Yiming Deng

May 15, 2013

Enfel, Barkat (M.S., Electrical Engineering)

Medium Access Control Using smart Antenna and Random-access algorithm For Multiple AD-HOC Wireless Networks

Thesis directed by Professor Titsa Papantoni

ABSTRACT

Interest in Smart Antenna Technology for wireless communication systems has increased in the recent years as a promising technique to improve the performance of cellular mobile systems. Considerable amount of research is being conducted to improve the performance of the system in terms of increasing the capacity and range. We discuss the different types of Smart Antenna systems using switched beam and adaptive antenna array techniques and describe how they can be used to implement in different multiple access schemes in wireless communications. A smart antenna's ability to simultaneously resolve simultaneous transmissions on the same channel is exploited to help expedite the process of random access. Intended for bursty data traffic, a random access Medium Access Control (MAC) protocol seeks to insure an orderly sequencing of packets from the various mobile stations onto the shared channel with minimum time lost to collisions. When applied to cellular radio systems, a MAC protocol must also cope with the various impairments suffered on the radio link such as multi-path fading, shadowing, and co-channel interference from other mobiles.

This thesis proposes to upgrade the performance of a class of random access protocols for wireless digital networks with smart antennas operating in the presence of Rayleigh slowly fading multipath transmission channels. The capture model assumed is a threshold model based on the signal to noise ratio, while the MAC protocol deployed is the two-cell random access algorithm, in a network environment where nodes are equipped with adaptive array smart antennas. The deployed protocol relies on the ability

of the antenna to deploy Direction of Arrival (DoA) algorithms, to identify the direction of transmitters and to subsequently beam-form accordingly for Signal- to Interference and Noise Ratio (SINR) maximization. The performance of the protocol is evaluated using analytical modeling as well as detailed simulations in Matlab, where we demonstrate the benefits of using smart antennas.

The form and content of this abstract are approved, I recommend its publications.

Approved: Titsa Papantoni

DEDICATION

I lovingly dedicate this thesis to my parents who supported me in each step of the way.

ACKNOWLEDGMENTS

I would like to thank my advisor Professor Titsa P. Papantoni for giving me a chance to be in the graduate program of the University of Colorado at Denver, Downtown campus, and for her support during the course of this work.

I am especially grateful to my dad Professor Mourad Barkat for his guidance, encouragement, and constant support during all my graduate studies and in particular for his assistance during the research and the preparation of the thesis.

I also thank professors Jan Bialasiewicz and Yiming Deng for serving on my thesis defense committee

I am also thankful to all my family, my mother and my brothers, for their support and encouragements.

TABLE OF CONTENT

LIST OF FIGURES

Figure

LIST OF TABLES

Table

1. General Introduction

Over the past few years, the demand for cellular communication applications such as internet access, multimedia data transfer and other wireless multimedia services witnessed a serious growth in third generation (3G) wireless communications systems. Thus, 3G wireless communications systems must provide a variety of new services with different data rate requirements under different traffic conditions, while maintaining compatibility with 2G systems.

In wireless communications, one of the major causes of radio interferences and energy use inefficiencies is the universally radiated antenna energy [1]. On the other hand, one of the several advantages of smart antenna deployment is their effect on the reduction of such interferences. Indeed, smart antennas have the capability of beaming in the direction of the desired signal, as means towards Signal to Noise Ratio (SNR) maximization due to the effective minimization (nulling) of the interfering signals [2]. In this thesis, we propose to upgrade the performance of a deployed MAC protocol via the use of smart antennas. In addition, we consider enhancing of the overall network performance via the deployment of a powerful MAC protocol. This study will discuss powerful random access MAC algorithms, in conjunction with smart antenna beam forming.

1.1 Literature Review

Smart antennas possess remarkable properties which may allow for relatively high throughputs in ad hoc network scenarios. Using a smart antenna with a transmitter enables the formation of a directed beam towards the receiver. On the other hand, the receiver forms a directed beam towards the sender, as well, resulting in a significantly high gain. By identifying the direction of arrivals from the multiple simultaneous transmitters using DOA algorithms, the receiver may also be used to determine the

directions where the nulls are to be placed. Consequently, nulls may be assigned correctly in the direction of interfering transmitters, to eliminate their impact [1, 2]. A lot of studies were conducted to develop the 802.11b - based MAC protocol with smart antennas, where beam-forming, DOA, and nulling were improved, to attain increased throughputs [3, 4]. In [5], Fung et *al*. [5] investigated the effect of smart antennas on the slotted ALOHA protocol with capture, in a mobile communications environment with Rayleigh and Log-normal fading. The original version of the slotted ALOHA is based on the assumption that the information in all packets will be lost if more than one packet is transmitted simultaneously due to possible collisions during transmission, where it was falsely considered that the slotted ALOHA throughput in the presence of an asymptotically large user population is nearly 0.36. To counter affect the lost packets due to collisions, the authors in [5] conducted a study using the "capture effect", allowing survival of the strongest signal in the presence of collisions. Their results demonstrate that by using a smart antenna system, higher performance in terms of capture probability and throughput is attained, as compared to a conventional antenna system.

In [6], Burrell and Papantoni-Kazakos presented a Class of limited sensing random access algorithms (RAAs) whose operations may be depicted by a stack. The algorithms are implementable and stable with maximum attained throughput 0. 429, in the presence of the limit Poisson user model. The authors also proved analytically and via simulation that, when an admission delay constraint on packet arrivals is imposed, the ALOHA – based Ethernet protocol performs insignificantly better than the limited sensing class algorithm for low traffic rates, while, as the input traffic rate increases, the two-cell random access algorithm in [6] outperforms the Ethernet protocol with an exponentially growing significance [7]. In [8], Yucel and Delic proposed a modified version of the two-cell random access algorithm which takes advantage of packet captures, in the presence

of a collision. They considered a mobile radio window random access algorithm (MRW-RAA), which augments the two – cell random access algorithm (TC-RAA) with diversity capability; they investigated its performance in a mobile environment with capture, fading, shadowing, and path loss. The power capture model based on the signal-to-interference ratio (SINR) was adopted and resulting significant throughput and signal to noise ratio values were also demonstrated.

1.2 Organization of the Thesis

The remaining of the thesis is organized as follows. In Chapter 2, we first present a review of spread spectrum communication using direct sequence code division multiple access (CDMA), present an overview of smart antennas and the use of the least mean square algorithm beam-forming. We also discuss random access algorithms. Chapter 3 contains our contribution; namely the use of smart antennas in a multiple interfering signal environment for a Rayleigh fading communication channel with the two-cell random access algorithm (TC-RAA) deployed for multiple access transmission.

2. An Overview of CDMA, Smart Antenna, and Random Access Algorithms

2.1 Introduction

In this chapter we give some background on direct sequence code division multiple access (DS-CDMA), random access algorithms, and smart antennas which are the three essential topics needed to understand the undertaken research in this thesis. In section 2.2 we present briefly the theory of spread spectrum communication. In Section 2.3 direct sequence code division multiple access (DS-CDMA) is introduced in some detail due to its importance in spread spectrum communication. The concept of smart antenna systems is introduced in Section 2.4 while in Section 2.5 we present random access algorithms.

2.2 Spread Spectrum Communication

The popularity of the Spread Spectrum communication has risen in the past years as a result of the development in the mobile phone industry. The development of the Spread spectrum systems was initiated in the mid-1950 for military communications with three main purposes:

- Hide sent signals,
- Secure the Signal and protect it from eavesdropping, and
- Provide a high resistance against Jamming.

Later, it was realized that Spread Spectrum systems could provide powerful and effective benefits to other civilian communications, such as, cellular mobile communications, timing and positioning systems and some specialized applications in satellites [9-11]. Those benefits include:

- Anti-interference,

- Multiple users access communications,
- High resolution ranging, and
- Accurate universal timing.

2.2.1 What is the Spread Spectrum Communication?

Spread spectrum communication is defined in [11] as: “Spread spectrum is a means of transmission in which the signal occupies a bandwidth in excess of the minimum necessary to send the information; the band spread is accomplished by means of a code which is independent of the data, and a synchronized reception with the code at the receiver is used for despreading and subsequent data recovery”. By this definition we understand that an independent pseudo noise (PN) code sequence is used for the spreading operation over a large bandwidth. The resulting wideband signal occupies a large band of frequencies embedded in noise in comparison to narrowband signals. This makes the wide band hard to jam and hard to be detected. A synchronized version of the PN code has to be used by the receiver in order to despread the received signal. Fig. 2-1 shows a block diagram of the spread spectrum communication system [12-13].

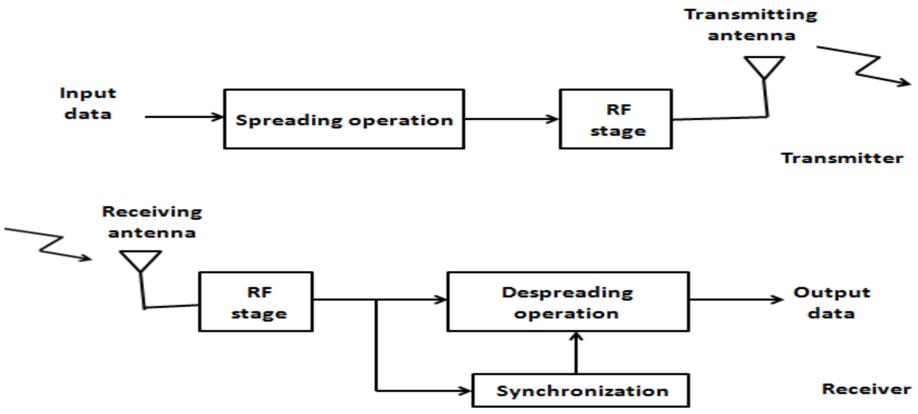

Fig. 2-1: Spread spectrum system.

2.2.2 Pseudo Noise Code Sequences

The Pseudo Noise code sequence or sometimes called pseudo random sequence is a noise-like (but deterministic) signal that is used for bandwidth spreading. It consists of 1's and 0's in a sequence creating the so called chips with a chip rate higher than the data signal's bit rate. This chips code sequence is generated satisfying the following properties [10, 13-14]:

(i) It is a periodic signal known to the transmitter and the receiver.

(ii) Its autocorrelation function has properties similar to the white noise signal, it has sharp autocorrelation peak (for that it is named pseudo noise). This property will help in the synchronization process.

(iii) It should be balanced, that is the difference between the number of 1's and 0's in each period should be at most one. With poor balance property, spikes will be seen in the spectrum so the signal will be easily detectable.

By applying this code sequence for spreading, the baseband narrowband signal will become a wideband and appears noise-like. The PN code sequence has many types; such as an m-sequence code, Gold code, and Hadamard-Walsh code. The PN code sequence will determine the bounds on the communication system capabilities, which makes it essential to select the appropriate code [14].

2.2.3 Types of Spread Spectrum Technologies

There are many spread spectrum technologies available these days. The most commonly used techniques are the direct sequence (DS) spread spectrum and the frequency hopping (FH) spread spectrum. Both of those techniques generate wideband signals controlled by the PN code sequences. On the other hand each technique employs the codes differently

in the spreading operation and the resulted spreading signals will be different as well. In the following, a description of those types of spread spectrum is given.

Direct Sequence Spread Spectrum Communication

The ease of implementation of the DS spread spectrum communication makes it the most commonly used technique. The narrowband data signal is spread by multiplying it directly with the PN code sequence and transmitted after being modulated. As a result of the data bit rate being lower than the chip rate, the signal will gain a large bandwidth as shown in Fig. 2-2. By considering the total signal power as the area under the spectral density curve, we realize that spreading the narrowband signal over a wide bandwidth will result in a reduced signal's power level (the power spectral density) and it becomes embedded in noise [12- 13].

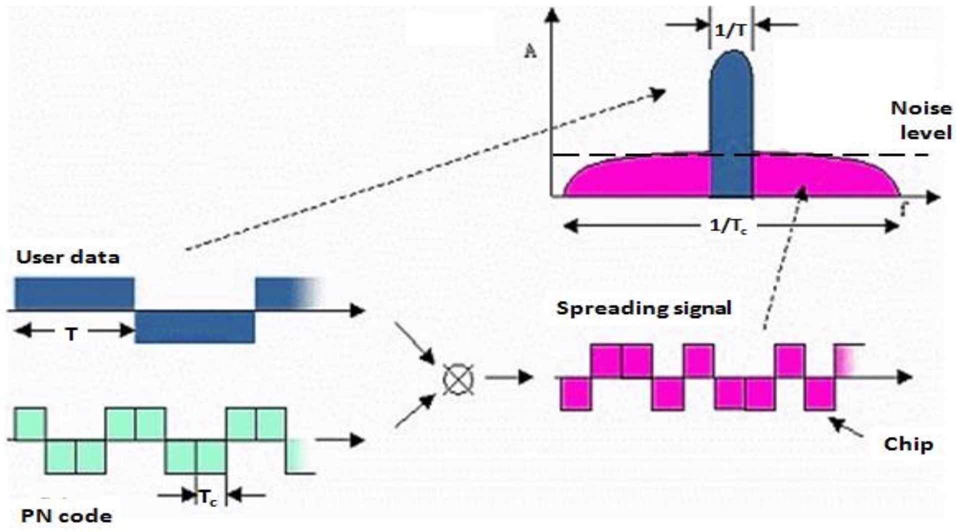

Fig. 2-2: Direct sequence spreading operation [12-13].

The whole large frequency band is continuously being occupied by the transmitted DS spread signal and its carrier stays at a fixed frequency. At the receiver, the local PN code sequence is multiplied with the received wideband signal so that the received signal

could be despread to obtain the original narrowband signal. However, if there is an interfering jamming signal, the multiplication with the PN code will spread it. As a result, the impact the jammer will be greatly reduced as shown in Fig. 2-3. This is one of the main reasons spread spectrum communication is less vulnerable to interferences [13].

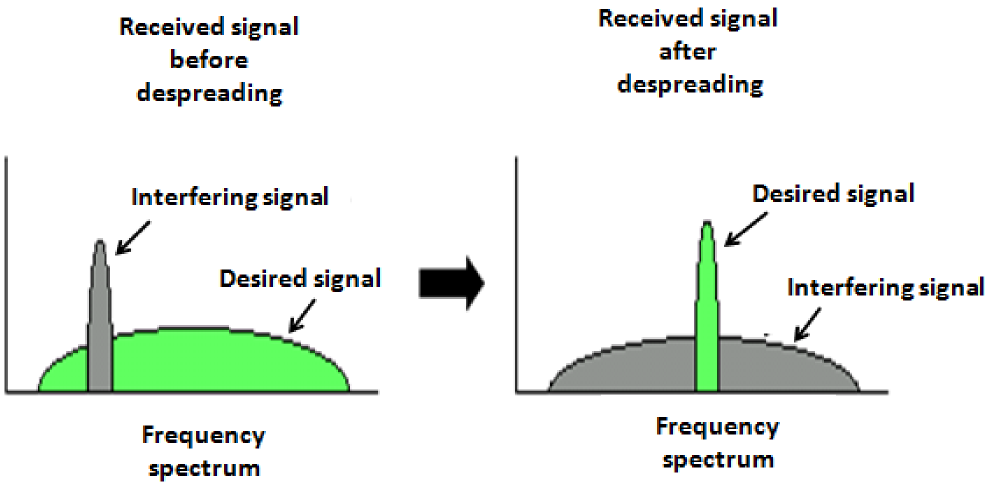

Fig. 2-3: Direct sequence despreading operation [website].

Frequency Hopping Spread Spectrum Communication

In frequency hopping (FH) spread spectrum, the spreading over a wide bandwidth is achieved by hopping from frequency to another frequency at regular time intervals within the large frequency band as shown in Fig. 2-4 and not by widening the total signal power of the narrowband signal as in direct sequence. Each user, in frequency hopping code division multiple access (FH-CDMA), will select one of available frequencies within the wide band channel as a carrier frequency. The Pseudorandom changes of the carrier frequencies randomize the occupancy of a specific band at any given time, thereby allowing for multiple accesses over a wide range of frequencies. A PN code sequence is used to shift the carrier frequency of the narrowband signal in a pseudo random manner [13].

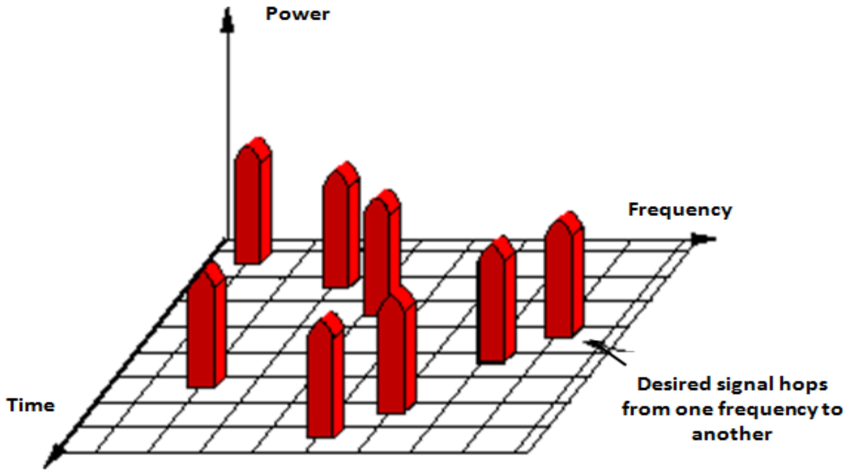

Fig. 2-4: Frequency hopping spread spectrum [website].

At the receiver, the synchronized PN code sequence is used to find out the different carrier frequencies at the variant time intervals. By hopping in short times between a large set of frequencies, the FH spread spectrum is capable of avoiding the location of a jamming signal. The DS spread spectrum has a higher jamming resistance compared to the FH spread spectrum. When there is a jamming signal in a frequency to which the signal will hop to it, a collision will occur and the data will be lost [12].

2.3 Code Division Multiple Access - CDMA

In direct sequence code division multiple access (DS-CDMA) each user will spread his signal by using a different PN code sequence which is (approximately) orthogonal to the PN codes of all other users. This will require that the receiver performs a correlation operation in order to detect the signal addressed to a given user. On the other hand, the low cross-correlation property will result in the other users' signals appearing as noise as shown in Fig. 2-5.

The focus will be on DS-CDMA since it is the most popular spread spectrum communication scheme used in today's CDMA technology, and which is considered in this thesis.

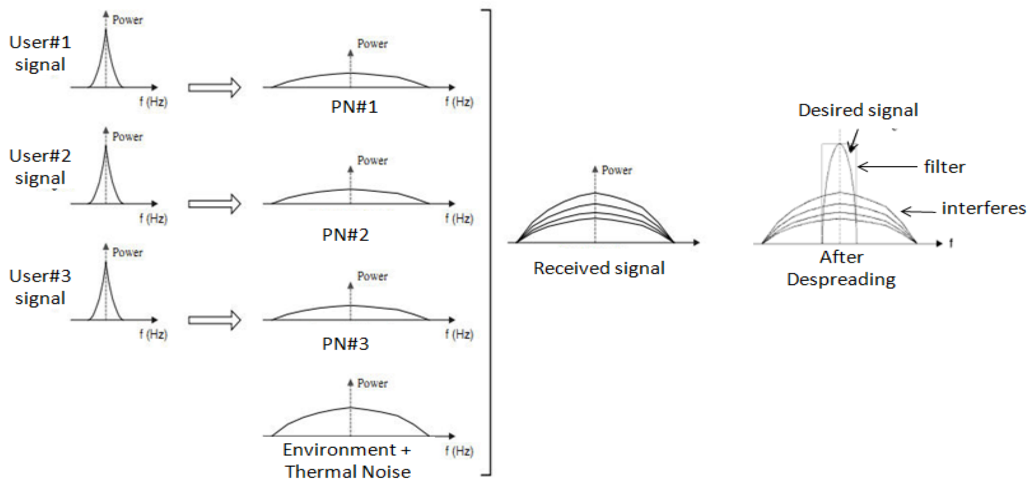

Fig. 2-5: DS-CDMA [15]

DS-CDMA Transmitter

A functional block diagram of the DS-CDMA transmitter is shown in Fig. 2.6

.

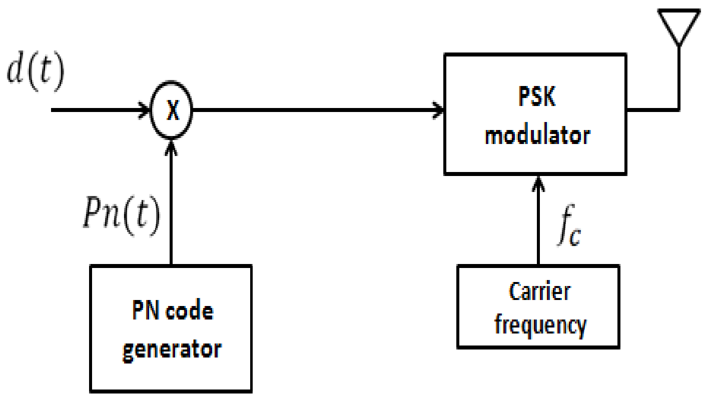

Fig. 2-6: DS-CDMA transmitter [13]

The transmitted signal $d(t)$ with a data bit rate R_d $(= 1/T)$ is first multiplied with the sender's PN code sequence $Pn(t)$ that has a chip rate R_c $(= 1/T_c)$ which is an integer multiple of R_d. The reason behind the multiplication is to spread the baseband bandwidth $BW_d \cong R_d$ of $d(t)$ over a large bandwidth $BW_{ss} \cong R_c$. After the spreading process, a PSK (phase shift keying) modulation is performed on the resulted baseband signal to transmit a bandpass signal with a pseudorandom phase shift. BPSK (binary PSK) and the QPSK (quadrature PSK) are commonly used for PSK modulation in practical systems [14].

DS-CDMA Receiver

In order to retrieve the data signal $d(t)$, the receiver needs to execute both despreading and demodulation operations on the received spreading signal. A synchronization process should take place before and during both operations, because these operations require a synchronized local PN code sequence $Pn(t)$ (for the despreading operation) and a synchronized carrier (for the PSK demodulation operation).

The need for synchronization process is a result of an initial timing and frequency uncertainty between the transmitter and the receiver for the following reasons [15]:

1. Uncertainty in the range between the transmitter and the receiver, which translates into uncertainty in the amount of propagation delay.
2. Relative clock instabilities between the transmitter and the receiver, which results in phase differences between the transmitter and the receiver spreading signals.
3. Uncertainty of the receiver's relative velocity with respect to the transmitter, which translates into uncertainty in a Doppler frequency offset value of the incoming signal.

4. Relative oscillator instabilities between the transmitter and the receiver, which results in frequency offset between the incoming PN sequence and the locally generated sequence.

According to the placement of the PSK in relation to the despreading process we have two models for DS-CDMA receivers. In the *non-coherent* receiver, the despreading of the received signal is done prior to the PSK demodulation as shown in Fig. 2-7.

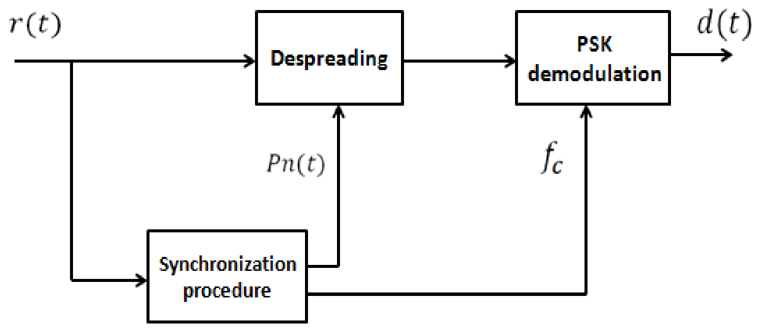

Fig. 2-7: Non-coherent DS-CDMA receiver [10]

On the other hand, in the coherent (synchronous) receiver the despreading process is performed after the PSK demodulation as shown in Fig. 2-8.

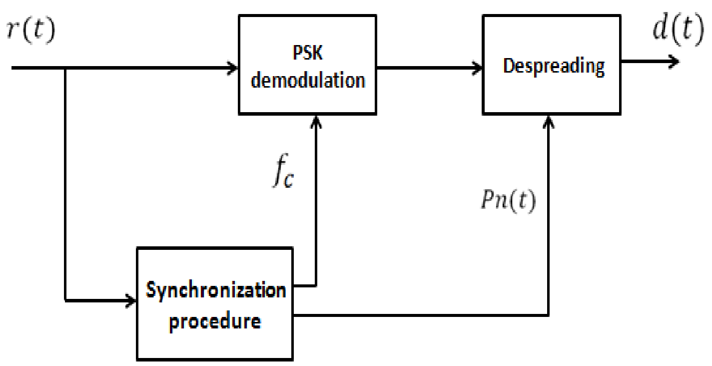

Fig. 2-8: Coherent DS-CDMA receiver [10]

PN Code Acquisition for Direct Sequence Receiver

The locally generated PN code sequence at receiver must be synchronized with the received PN code sequence to be able to despread the received signal in a spread spectrum communication system. The Synchronization process has to be done within a small fraction of chip duration. Otherwise, due to the orthogonality principle, inadequate signal energy will reach the receiver data demodulator. Synchronization is performed normally in two stages: the first stage is the PN code acquisition stage and the second stage is the PN code tracking.

In the PN code acquisition the two PN codes are brought into coarse time alignment to within a fraction of the chip duration. The PN code tracking process is initiated as soon as the PN code acquisition is achieved. The PN tracking process aims to reducing the synchronization errors to an acceptable limit for maintaining the two PN codes in fine synchronism [10, 16].

The PN code acquisition process could be looked at as an attempt to synchronize the receiver clock to the transmitter clock. Despite of using extremely accurate clocks in spread spectrum communication systems to reduce the time uncertainty between the receiver and transmitter clocks, the propagation delay in the transmitted signal through the channel and the propagation effects such as multipath result in and uncertainty at the receiver about the timing (phase) of the received PN code sequence. This time uncertainty region, a region of all possible phases of the received PN code sequence, is typically divided into a limited number of cells. Each of these cells corresponds to a different phase delay and the receiver must determine which individual cell is the phase of the received PN code sequence. This means that during the synchronization (acquisition) stage, the receiver searches through those potential code phases, evaluates each phase and then test

it by attempting to despread the received signal. Then dispreading of the received signal will only occur if this tested code phase is correct (i.e. synchronized code phase). Otherwise, in case of incorrect phase, the received signal will not be despread [10].

The acquisition process could be presented as a binary hypothesis problem. If we achieve synchronization then we have hypothesis H_1; otherwise, we have the null hypothesis H_0 in the tested code phase. Making a decision in favor of hypothesis H_1 or hypothesis H_0 is done by the receiver. This decision is based on some criterion in favor of *Detection* when the tested code phase is truly the synchronized code phase. Also the receiver will decide in favor of H_0 hypothesis when the tested code phase is truly in non-synchronization situation is a correct rejection. A *false alarm* is When the receiver makes a decision in favor of hypothesis H_1, while actually H_0 is true. Deciding in favor of hypothesis H_0 when H_1 is true is referred to as a *miss*. The probability of the first wrong decision called the probability of false alarm (P_{fa}) while the probability of the second wrong decision called the probability of miss (P_M). This terminology is borrowed from the radar nomenclature [10].

Scanning the cells (code phase) could be done through several search strategies in the uncertainty region for PN code acquisition. First, the received and local PN code signals are multiplied so that a measure of the correlation between these two codes is produced. We could obtain this measure either by using an active correlator or a passive matched filter. In the case of the active correlator, the received PN code signal is multiplied with a continuously running local generated PN code signal. After that the signal is integrated over a time interval often called the dwell time to get the correlation measure. In the passive matched filter, the received PN code signal is convolved with a fixed local PN code signal. In this configuration, the input continuously slides past the

stationary (not running in time) local PN code until the two are in synchronism. The next step is passing the obtained correlation measure to a suitable detector/decision rule to detect if the two codes are synchronized or not for the tested code phase. The dissimilarities between the various PN code acquisition schemes depend on both: the type of detector (decision strategy) used and the used search strategy which works on the detector outputs to make the final decision. Therefore, we could classify PN code acquisition schemes in various ways based on the detectors and the search strategies. Typically the noncoherent detector is used detector for acquisition in DS-CDMA communication receivers in which the despreading operation is performed before the carrier phase synchronization [16].

2.4 Smart Antenna Systems

A smart antenna is defined as an array of antenna elements with a digital signal processing unit that can change its pattern dynamically to adjust to noise, interference and multipath. A block diagram of a smart antenna system is shown in Figure 2.9.

The following three main blocks are identified:

(i) Array antenna

(ii) Complex weights and

(iii) Adaptive signal processor.

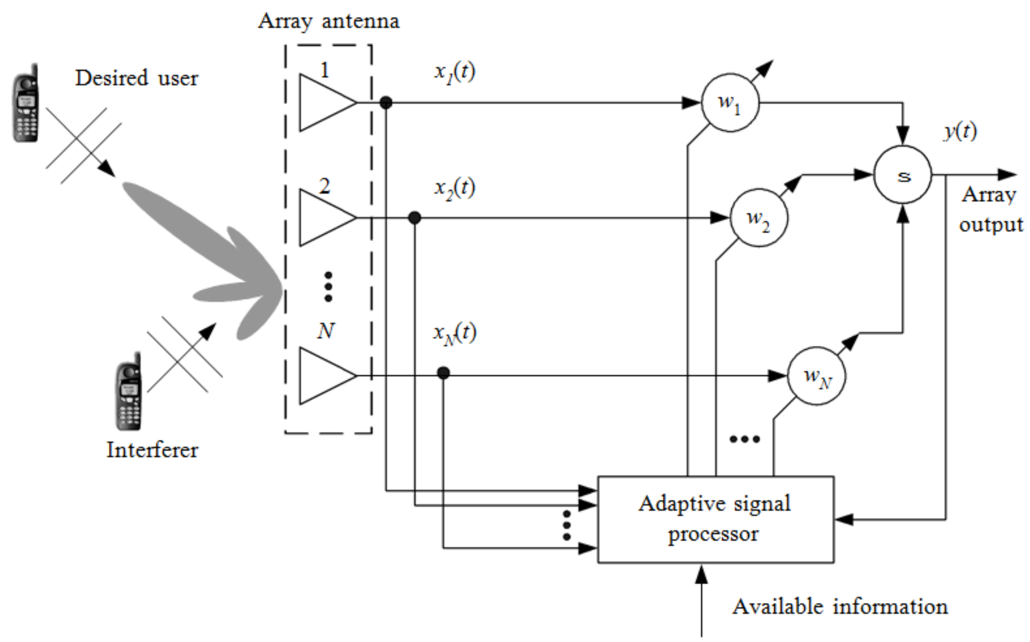

Figure 2.9 Block diagram of a smart antenna system

The term smart antenna refers to the whole antenna system as mentioned above and not only the array antenna. The array antenna consists of antenna components/elements in a Uniform linear Array (ULA) or Uniform Circular Array (UCA) of antenna elements, and those individual elements are the same in the omni-directional patterns in the azimuth plane. In order for the main beam to track the desired user, nulls are placed in the direction of interference and/or the complex weights $w_1, w_2, \cdots, w_N$, are continuously adjusted by the adaptive signal processor. The signals received at the different antenna elements are multiplied with the complex weights and then summed up.

2.4.1 Classification

The underlying idea and first studies proposed for smart antennas is relatively old and dates back to the 1960's, where it was intended to be as a counter measure to jamming [17]. Cost has always played a role in preventing smart antennas to be used commercially until the recent technologies made it possible and practical to use smart antennas commercially. As illustrated in Figure 2.10, the smart antenna systems may be

divided into three main categories:

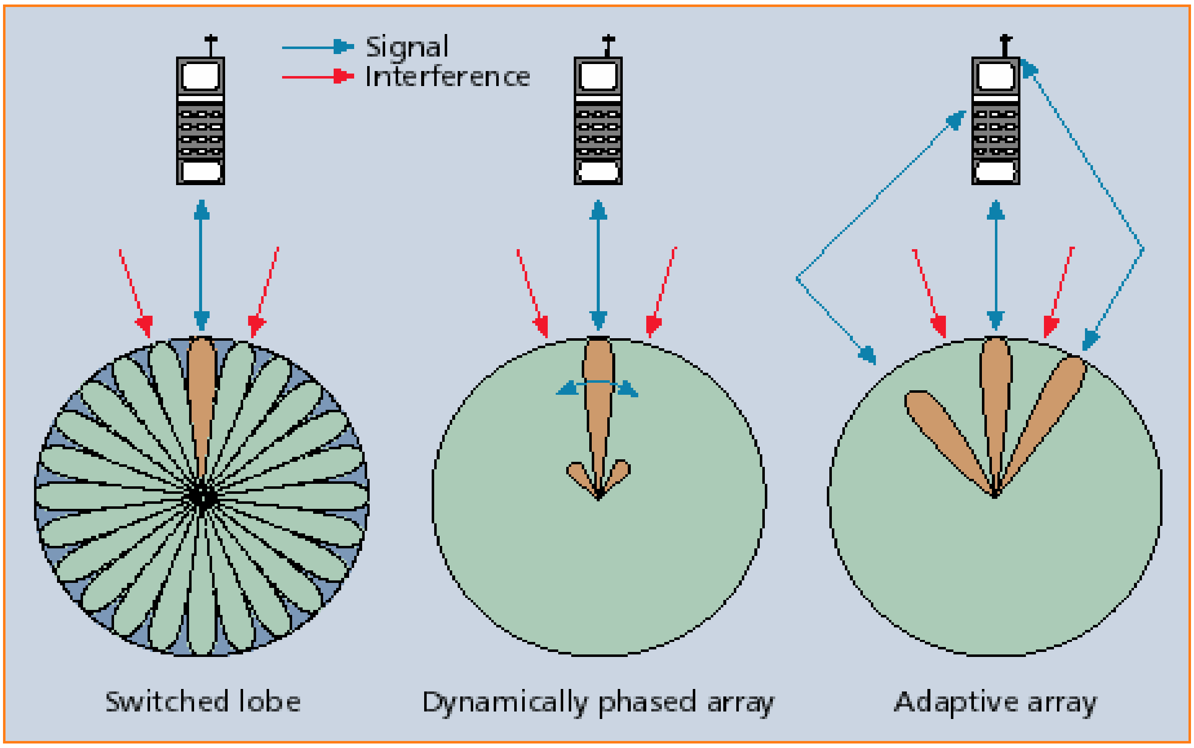

Figure 2.10 Different classifications of smart antenna systems [9]

(i) Switched beam systems

(ii) Phased arrays

(iii) Adaptive arrays.

It has to be noted that this division is not rigid, where switched beam and phased array systems are simpler physical approaches to realising fully adaptive antennas.

Switched Beam Systems

A switched beam antenna system is made out of highly directive, fixed, pre-defined beams which can be formed by means of a beam-forming network containing power splitter and phase shifter as shown in Figure 2.3. The setting chosen is the factor contributing to the best performance, usually in terms of received power. Switch beam

antennas are not capable of distinguishing a user from an interferer, depending on the distance from the center of a selected beam, where this defect limits their use to low or moderate co-channel interfering surroundings.

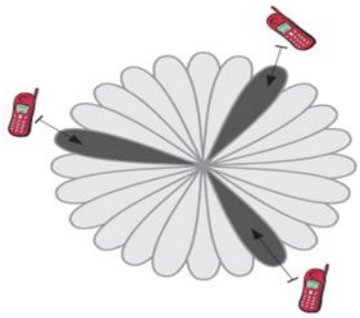

Figure 1.11 Switched beam smart antenna system [9]

Phased Arrays

Phased arrays rely on the Angle of Arrival (AOA) information for source direction. Weighing and combining of the signals is performed to create a beam in the mobile direction where the phases of the weights are varied and the amplitudes are held constant. Although phased arrays are considered an improvement of the capabilities of the switched beam antennas, they have certain constraints that could be overcome by the implication of fully adaptive arrays.

Adaptive Antennas

Unlike the phased arrays system, the adaptive array systems use beam steering and nulling and are capable of providing greater received signal gain but they have a higher initial cost. Fully adaptive systems rely on the use of advanced algorithms to discover and trace a specific signal. To be able to get the maximum result for a specific measure, such as Signal to Interference plus Noise Ratio (SINR) or the Signal to Noise Ratio (SNR), magnitude and phase are used in weighing and combining the signals received. Figure 2.12 shows the beam pattern of a switched beam and an adaptive array.

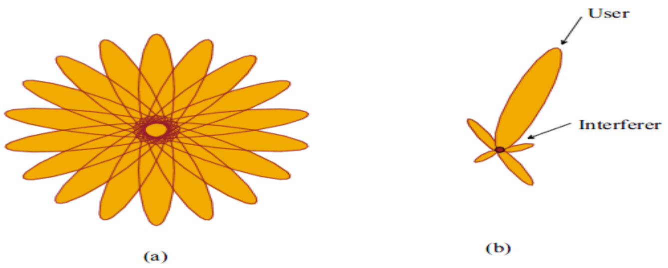

Figure 2.12 Coverage pattern: (a) switched beam, (b) adaptive array [9]

2.4.2 Benefits of Smart Antennas

The application of smart antennas plays a major role in improving wireless and sensors applications. The abilities of the systems may improve via the use of smart antennas, where narrow beams are directed to target the desired user and to simultaneously null other undesired users. This results in higher signal-to-interference ratios and decrease of power levels, allowing for a higher frequency reuse within the same cell.

The majority of the base stations in the United States use the concept known as *Space Division Multiple Access* (SDMA), which divides into three 120 swaths. This division magnifies the system capacities and could potentially triple them within a single cell. The increase in the capacities results from the users sharing the spectral sources in each of the three sectors. By modifying base stations and implementing smart antennas, the 120 sectors could be subdivided even more, resulting in less power level requirements, greater bandwidth and higher system capacities. Another advantage of using smart antennas is the possible reduction and/or elimination of the damaging effects of multipath by using a constant modulus algorithm to control the smart antenna and null multipath signals. As a result, both a reduction in the fading of received signals as well as higher data rates could be achieved relying on the capability of smart antennas to reduce co-channel interference as well as multipath fading.

The improvement of direction-finding (DF) techniques by finding the angles-of-arrival (AOA) more accurately is another important benefit of smart antennas. Accurately determining the AOA plays a very important role in imaging objects or tracking objects in radar systems.

Smart antenna implementation has also other benefits in Geo-Location services, Multiple Input-Multiple Output (MIMO) communications systems as well as waveform diverse MIMO radar systems. In Geo-Location services the DF capabilities of smart antennas allows a more accurate location of the mobile user. Smart antennas are also capable of directing the array main beam toward signals of interest even when no reference signal or training sequence is available, which is known as blind adaptive beam forming. Smart antennas have also a major benefit in altering radiation patterns which results in better capitalizing on the presence of multipath, because of the transmission of various waveforms from each of the elements in the transmit array and combining them at the receive array. On the other hand, implementation of smart antennas with MIMO radar will result in improved performance, increase array resolution and reduce clutter by exploiting the independence between the various signals at each array element.

In summary, let us list some of the numerous potential benefits of smart antennas:

- Improved system capacities
- Higher permissible signal bandwidths
- Higher signal-to-interference ratios
- Increased frequency reuse
- Sidelobe cancelling or null steering
- Multipath mitigation
- Blind adaptation
- Instantaneous tracking of moving sources

- Clutter suppression
- Improved array resolution

2.5 Random Access Algorithms

Random access techniques are considered for environments where the identities of the users may vary and are generally unknown. These techniques range from the pure ALOHA technique, where a user transmits whenever it has a message to deliver to some destination and retransmits with some pre-assigned probability, to sophisticated techniques where arrival time windows are selected and where retransmissions follow relatively elaborate rules.

In this thesis, we focus on the "random-access" approach for the accessing of a single, errorless, slotted channel, by independent, identical, packet transmitting, bursty users. The global properties of the user/channel model considered are as follows [7]:

- All transmitted packets have identical lengths each requiring the length of a single slot for transmission.
- The transmission by all users is synchronous, where they are allowed to start transmission only at the beginning of some slot; and there are no propagation delays in the channel feedback information obtained by the users.
- If at least two packets attempt transmission within the same slot, a collision occurs and such an event is initially the only cause for faulty transmissions; that is, a slot occupied with a single packet results in successful transmission, while a collision results in complete loss of the information carried by the collided packets. Thus, retransmission of collided packets is then necessary.

- The outcome per slot possibly accessible by the users—named *feedback level*—is either binary, distinguishing between Collision (*C*) versus Non-Collision (*NC*), or ternary, distinguishing between collision (*C*), versus emptiness (*E*) versus success (*S*).

We note that an *NC* event corresponds to a slot that is either empty or occupied with a single packet transmission, while an *S* event corresponds to a slot occupied with a single packet whose transmission is then successful. The accessibility of the feedback level outcomes by the users—named *channel sensing*—is a characteristic of each Random Access Algorithm (RAA) and specifies the time instants (in slots) when each user is required to sense the feed-back level outcomes (accessible by either channel sensing or broadcasting). Based on channel sensing requirements, the existing RAAs may be classified as members of one of the three distinct channel sensing classes be-low [6]:

- *Minimal Sensing RAA Class*: Each user is required to sense the feedback level outcome of only those slots within which it transmits.
- *Limited Sensing RAA Class*: Each user is required to sense continuously the feedback level outcomes of all slots from the time instant when a packet is generated to that when the packet is successfully transmitted.
- *Full Sensing RAA Class*: Each user is required to know the overall feedback history of the channel, from the be-ginning of time and even before the user became part of the system.

Regarding user population models, the following distinction will be necessary in our presentation [6]:

- *Known User Population Model*: The identities of all users are distinct and known to the system. This class implies finite membership.

- *Unknown User Population Model*: The identities of the users are unknown to the system, usually due to time- varying user characteristics. The membership of this class may be either finite or infinite.

- *Limit Poisson User Population Model*: Infinitely many identical Bernoulli users, comprising an aggregate Poison packet generating process, where each packet is a separate user. This is a special case of the unknown user population model.

2.5.1 Fundamental Concepts and Throughput Computation

Random Access Algorithms (RAAs) are deployed when the user population is unknown. In the study of RAAs, the fundamental concepts arising that also characterize their performance are the system stability and induced delays. Given some RAA and given the user population, we define throughput and per packet delay as follows [7]

- T*hroughput*: The maximum aggregate packet traffic rate for which the user/RAA system is stable.

For throughput computation we follow the following steps:

(a) Given the user model, identify appropriate measure of system backlog.

(b) Consider the beginnings A and B of two consecutive CRIs, where A precedes B, and let SA and SB denote the backlogs at A and B respectively.

(c) Require that the expected value of the backlog growth at B be negative; that is, $E\{SA\} - SA < 0$

(d) In the throughput expression in (c), the computation of the expected length of a CRI is required. Derive the tight bounds that may be needed in this computation.

(e) Use the result from step (d) to compute the value of the throughput.

- *Per Packet Delay*: The distance in slot units between the arrival instant of a packet arrival and the instant when its transmission has been completed.

At the same time, studies of error sensitivity correspond to identifying the effect of feedback errors on the throughput of the user/RAA system.

2.5.2 The Limited Sensing Initialization Process for the Limit Poisson Population

Packet-transmitting user, a slotted channel, binary collision virus-non-collision (C-NC) feedback, zero propagation delays and no feedback error are assumed. Also collided packets are fully destroyed and retransmission is necessary. x_t denotes the feedback that corresponds to slot t. The user is supposed to sense the channel from the time the packet is generated till the time it is successfully transmitted (LS). Each algorithm in this class utilizes a window of size Δ to optimize the selection of throughput optimization and induces a selection of collision resolution intervals (CRI) that its length is determined by the number of users in the window Δ.

K-cell algorithm

This algorithm has a collision resolution process that can be depicted by a stack with finite number of cells K. Then, in the implementation of the collusion resolution process each user utilizes a counter whose value lies in the set of integers $[1,2 \ldots k]$. We denote by r_t the counter value of a user in slot t. When the CRI begins, all the users in the window Δ set their counter values to 1. When its counter value is 1, the user transmits; otherwise he withholds at $(K-1)$ different stages. The transition of the counter values in time are as follows:

If $x_{t-1} = NC$ and $r_{t-1} = j;\ j = 2,3, \cdots, K$, then $r_t = j - 1$

If $x_{t-1} = C$ and $r_{t-1} = j;\ j = 2,3, \cdots, K$, then $r_t = j$

If $x_{t-1} = C$ and $r_{t-1} = 1$ then

$$r_t = \begin{cases} 1; & w.p.\,1/K \\ 2; & w.p.\,1/K \\ 3; & w.p.\,1/K \\ & \vdots \\ K; & w.p.\,1/K \end{cases}$$

As a consequence of the above transitions, a CRI which starts with a collision slot ends with K consecutive non-collision slots, and this event cannot occur at any other instant during the CRI. Thus, the event of K consecutive NC slots signifies either the ending of a CRI which started with a collision or the occurrence of K consecutive trivial CRIs. In either case, upon the occurrence of the K consecutive NC slots event, a new packet arrival is assured of the ending of a CRI and synchronizes then with the algorithmic operations on the deployed RAA. Subsequently, the packet generates a sequence of arrival updates, as induced by the algorithmic window size parameter Δ, until it participates in the collision resolution process of some CRI during which the packet is successfully transmitted.

2.5.3 Conclusion

In this chapter we have presented a review of spread spectrum communication with a focus on direct sequence code division multiple access (DS-CDMA), which is the most popular technique in today’s technology wideband communications. We also presented a brief review of smart antennas and discussed some principles of random access algorithms. Some key definitions and some related performance criteria, as well as a class of RAAs were also presented in some detail.

3. The Smart Two-Cell Algorithm

3.1 Introduction

We present a system containing M smart antennas, multiple users, a main user and interfering signals. The communication channel model assumed is a Rayleigh slowly fading multipath channel. We first apply the Least Mean Square (LMS) algorithm to optimize the weights for better signals to be used for the TC-RAA algorithms.

3.2 Communication System Considered

The CDMA communication system model for multiple users and using smart antenna was proposed by Sofwan and Barkat in [18] and is shown in Fig. 3.1. A linear array with M elements spaced equally to one half of the carrier wavelength is assumed $(d = 0.5\lambda)$. We also assume that D users transmit simultaneously, but the first user is assumed as the initial synchronization user whose performance is to be evaluated.

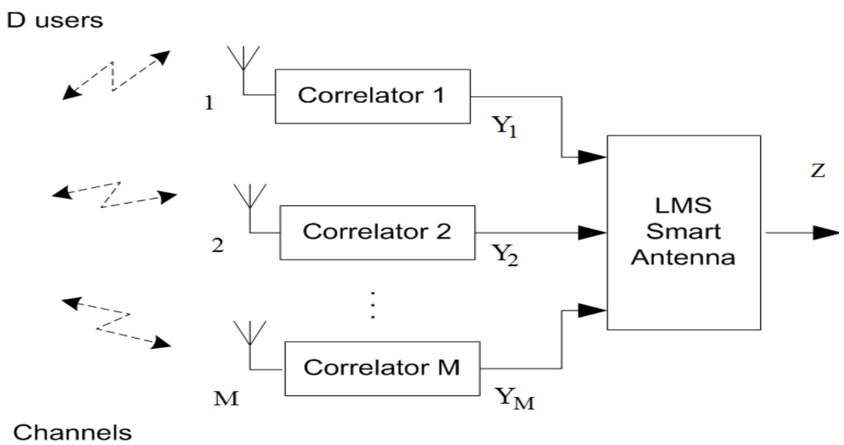

Figure 3.1 Block diagram of the proposed communication system model

The transmitted signal of the ith user is given by

$$S_i(t) = \sqrt{2P_i} b_i(t) c_i(t) \exp[j(\omega_c t + \varphi_i)] \tag{3.1}$$

where

P_i is the transmitted power of the ith signal,

b_i is the data waveform,

$c_i$is the spreading sequence of the i^{th} user,

ω_c is the common angular carrier frequency, and

φ_i is the phase of the ith modulator from the transmitter.

The user signals are sent through a communication channel assumed to be a Rayleigh slowly fading multipath channel. The transmitted signals are received by an antenna array of M elements and go through an LMS processor. The transmitter aids the initial synchronization by transmitting an unmodulated PN sequence $b_1(t) = 1$.

3.2.1 Channel Model

The mobile radio channel considered consists of L tapped delay lines that correspond to the number of resolvable multipath with amplitudes α_{il} and phases $\varphi_{il}, i = 1,2,\cdots,D$, and $l = 1,2,\cdots,L-1$. The probability density function (pdf) of the independent and identically distributed (i.i.d.) Rayleigh random variables is given by [10, 18]:

$$f_{\alpha_{il}}(x) = \frac{2x}{\sigma_f} \exp\left(-\frac{x^2}{\sigma_f^2}\right), \quad x \geq 0 \tag{3.2}$$

where $\sigma_f^2 = E[\alpha_{il}^2]$ is the average fading power in each path and is defined as [19]

$$E[\alpha_{il}^2] = \frac{1-e^{-\mu}}{1-e^{-\mu L}} e^{-(l-1)\mu}; \;\; \mu \neq 0, l = 1,2,\cdots,L \tag{3.3}$$

and μ represents the multipath intensity profile. The receiving antenna array consists of M identical elements spaced d apart, where $d = 0.5\lambda_c$ and λ_c is the wavelength of the carrier transmitted signal. Hence, the response vector of the antenna array can be expressed as

$$\boldsymbol{\alpha}(\theta) = [1 \quad e^{-j\pi \sin\theta} \quad \ldots \quad e^{-j\pi(M-1)\sin\theta}]^T \tag{3.4}$$

where $\boldsymbol{\alpha}(\cdot)$ is the array vector of antenna, θ is the direction of arrival (DOA) angle of the desired signal, and Tdenotes transpose. LMS is an adaptive array antenna algorithm which adapts its weight vector iteratively to any array response vector. The received signal consists of the signal from the first user, multiple access interferences from the others, and an additive white Gaussian noise (AWGN) $n(t)$. Thus, the received signal at the mth antenna element of the array is [18]

$$\begin{aligned} r_m(t) = \sqrt{2P_R} &\left\{\sum_{l=0}^{L-1} \alpha_{1l} c_1(t-\tau_1-lT_c) e^{j(\omega_c t+\varphi_{il})} e^{-j\pi(m-1)\,sin\,\theta_s}\right\} \\ &+\sqrt{2P_I}\left\{\sum_{i=2}^{D}\sum_{l=0}^{L-1} \alpha_{il} b_i(t-\tau_i-lT_c) c_i(t-\tau_i-lT_c) e^{j(\omega_c t+\varphi_{il})} e^{-j\pi(m-1)\sin\theta_i}\right\} \\ &+n_m(t)\,; m = 1,2,\cdots,M \end{aligned} \tag{3.5}$$

where P_R is the received signal power of the first user during initial synchronization, P_I is the received signal power of each interfering user, τ_i is the relative time delay associated with the asynchronous communication channel model, $\phi_{il} = \varphi_i - \varphi_{il} - \omega_c(\tau_i + lT_c)$ are independent and identically distributed (*i. i. d.*) random variables uniformly distributed over the interval $[0, 2\pi)$, T_c is the chip duration, θ_s is the DOA of the first user, and θ_i is the DOA angle of the interfering user. We assume $D-1$ interfering users are

transmitting. Note that the received signal is composed of three parts: the received signal from the first user, multiple access interference (MAI) from the other $D-1$ and the additive white Gaussian noise.

3.2.2 Correlator Output

In this section, we give the probability function of the in-phase and quadrature phase $(I-Q)$ components at the output of the active correlator for each of the m branches as shown in Fig 3.2.

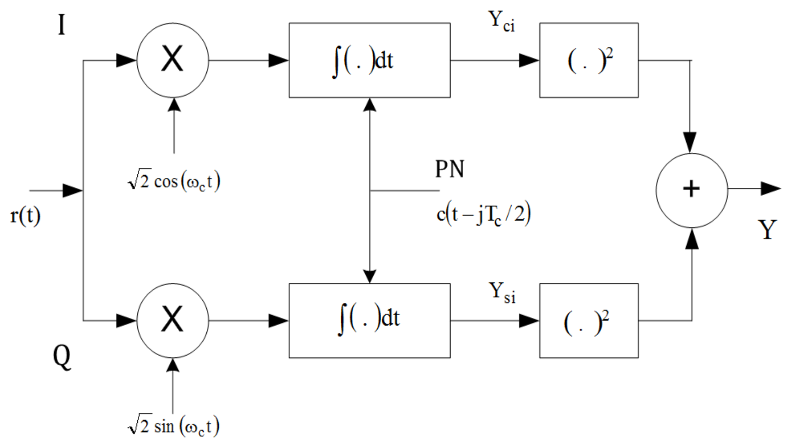

Figure 3.2 Correlator consisting of in-phase (I) and quadrature-phase (Q) components

Based on the following assumptions:

(i) The search step size is $T_c/2$

(ii) The dwell time is $\tau_D = RT_c$ with $R \gg 1$ so that the correlation between the received signal and the locally generated PN code is zero when they are not aligned.

(iii) The multiple access interference (MAI) from the other $D-1$ and the self-interference caused by the $L-1$ resolvable paths.

The output Y represents either a hypothesis H_1 denoting alignment of the received signal and the local PN code, which yields a high correlation value; or hypothesis H_0 denoting a non-alignment of the received signal and the local PN code with a negligible correlation value. When the output Y presents the aligned hypothesis H_1, we consider the branch values Y_{ci} and Y_{si} follow a non-central Chi-square distribution law with two degrees of freedom, then the pdf of Ygiven the amplitude of first user path α_{1l} can be written as [18]:

$$f_{Y|\alpha_{1l}}(y|\alpha_{1l}, H_1) = \frac{1}{2\sigma_0^2} \exp\left(-\frac{\lambda^2 + y}{2\sigma_0^2}\right) I_0\left(\frac{\sqrt{\lambda^2 y}}{\sigma_0^2}\right), \quad y \geq 0 \tag{3.6}$$

where σ_0^2 is the variance, and λ^2 is the normalized non-central parameter given by $\lambda^2 = 9/16\alpha_{1l}^2$.

Gaussian approximation was considered to represent the self-interference, the multiple access interference, and the thermal noise of the proposed system. We use the self-interference variance σ_s^2, the multiple access interference variances σ_M^2, and thermal noise variance σ_N^2 as defined by

$$\sigma_s^2 = \frac{\psi}{3R} \tag{3.7}$$

$$\sigma_M^2 = \frac{\beta\psi}{3R} \tag{3.8}$$

$$\sigma_N^2 = \frac{1}{2RS_c} \tag{3.9}$$

β represents the average received power of the interfering signal to the signal power of the first user ratio, and β is defined as

$$\beta = \frac{P_I}{P_s} \tag{3.10}$$

while S_c represents the $SNR/chip$ and is given by

$$S_c = \frac{T_c P_s}{N_0} \tag{3.11}$$

Since the proposed communication system considers L multipath and D users, there are $L-1$ paths scattering of the first user and $D-1$ of other users. The I component of correlator has variance σ_0^2 that consists of $(L-1)\sigma_S^2, L(D-1)\sigma_M^2$, and σ_N^2. Similarly, the Q component has also the same variance σ_0^2.

The pdf of the aligned hypothesis is calculated by substituting equations (3.2) and (3.5) to the Bayes theorem as follows:

$$f_{Y|H_1}(y|H_1) = \int f_{Y|\alpha_{1l}}(y|\alpha_{1l}, H_1) f_{\alpha_{1l}}(\alpha_{1l}) d\alpha_{1l} \tag{3.12}$$

After mathematical calculations, the pdf of the aligned hypothesis may be expressed as [18]

$$f_{Y|H_1}(y|H_1) = \frac{1}{2\sigma_0^2(1+\nu)} \exp\left[-\frac{y}{2\sigma_0^2(1+\nu)}\right], \quad y \geq 0 \tag{3.13}$$

where

$$\nu = \frac{9}{32}\frac{\sigma_f^2}{\sigma_0^2} \tag{3.14}$$

When the output Y constitutes the non-aligned hypothesis H_0, it follows the central Chi-square distribution law with two degrees of freedom. The pdf of Y corresponding to H_0 can be expressed as

$$f_{Y|H_0}(y|H_0) = \frac{1}{2\sigma_0^2} \exp\left(-\frac{y}{2\sigma_0^2}\right), \quad y \geq 0 \tag{3.15}$$

3.2.3 Smart Antennas

Smart antenna in the proposed system which performs adaptive beam-forming by using the LMS algorithm for directing the main array pattern towards the preferred source signal and for creating nulls in the directions of the interfering signals [20]. The LMS algorithm computes iteratively the optimum beam-forming weight vector iteratively, utilizing the Minimum Squares Error (MSE) criterion between the desired signal value and the LMS processor output. We select the LMS algorithm because of its benefits such as simplicity, ease of implementation, good accuracy, and good convergence properties. The outputs $\boldsymbol{Y}_m, m = 1,2,\cdots,M,$ from the M branches of the correlator are inputs to the LMS processor as shown in Fig. 3.3, are then denoted as follows

$$\boldsymbol{Y}_m(n) = [Y_1(n) \quad Y_2(n) \quad \cdots \quad Y_M(n)]^T \tag{3.16}$$

where n is a number of iterations until convergence is reached.

The beam-forming weighting maximizes the output from the LMS processor by adapting the beam-forming weight vector $\boldsymbol{w}_m, m = 1,2,\cdots,M,$ directly proportional to the step size parameter μ. We assume a step size of $\mu = 1/M$ for achieving convergence. Moreover, we also assume that the desired signal power $d(n)$ with the optimum weight equals M, and thus the error signal is expressed as

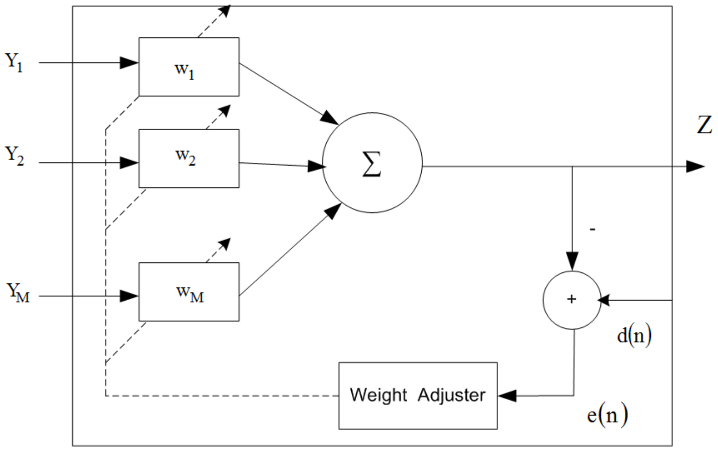

Figure 3.3 LMS processor

$$e(n) = M - \boldsymbol{w}_m^H(n)\boldsymbol{Y}_m(n) \tag{3.17}$$

The value of $e(n)$ is used by the LMS processor to adjust $\boldsymbol{w}_m(n)$ adaptively so that MSE is achieved. The iterative procedure of the LMS processor is given by

$$\boldsymbol{w}_m(n+1) = \boldsymbol{w}_m(n) + \mu e^*(n)\boldsymbol{Y}_m(n) \tag{3.18}$$

Once the minimum MSE is attained, then this weight vector is used to generate a spatial correlation output Z. If the output Y_m of the considered correlator is under the aligned hypothesis, then theoretically we say the weight vector is optimum. In other words, we assume that DOA of the desired signal can be located optimally by the smart antenna and thus the pdf of the aligned hypothesis is then [18]:

$$f_{Z|H_1}(z|H_1) = \frac{1}{2\sigma_0^2(M + M^2\nu)}\exp\left[-\frac{z}{2\sigma_0^2(M + M^2\nu)}\right], \quad z \geq 0 \tag{3.19}$$

Contrarily, if the output Y_m of the correlator is under a non-aligned hypothesis, then we assume that the smart antenna tracks in a different angle from the desired signal. The pdf of the non-aligned hypothesis is given by

$$f_{Z|H_0}(z|H_0) = \frac{1}{2\sigma_0^2 M} \exp\left[-\frac{z}{2\sigma_0^2 M}\right], \quad z \geq 0 \tag{3.20}$$

3.3 Two-Cell Random Access Protocol

In our system model [6], we assume slotted channel, packet-transmitting users, zero propagation delays, initial absence of feedback errors and that the collided packets are totally destroyed which makes retransmission necessary. We also assume binary collision-versus-non-collision (C-NC) feedback after each slot where slot units correspond to time intervals defined as follows: slot t occupies the time interval $[t, t+1)$ where x_t designates the feedback corresponding to slot t; $x_t = C$ and $x_t = NC$ express the collision and non-collision events in slot t, respectively.

Algorithms are implemented independently by each user in the class. The users' knowledge of the feedback history is said to be asynchronous because each user will only need to monitor the channel feedback after generating a packet to the time this packet is transmitted successfully. Whether or not a collision resolution is in progress within a limited number of slots will be decided by each user and such decision could only be induced by the unique operational characteristics of each algorithm in the class. This would also help in preventing the interference from new arrivals occurring within the duration of a collision resolution process.

Individual algorithms in the class employ a window of size Δ as an operational parameter and induce a sequence of consecutive Collision Resolution Intervals (CRIs). Maximizing the throughput is the main criterion in selecting the window length Δ. Each Collision Resolution Interval corresponds to the successful transmission of all packet arrivals within an arrival interval of length Δ, where the number of packet arrivals in this interval and

algorithmic steps of the collision resolution process are the key factors in determining the length of each Collision Resolution Interval (CRI). The packet arrivals asynchronously determine the placement of the Δ-size window.

The two-cell algorithm is a member of the class of K-cell stack random access algorithms, where K is an integer larger than or equal to 2. For fixed K value, the operations of the K-cell stack random access algorithm may be depicted by a stack containing K cells, in conjunction with a counter which points to the various cells of the stack during the collision resolution process. In particular, in the implementation of the collision resolution process, each user uses a counter whose values lie in the set $[1, 2, 3, \ldots, K]$ where r_t denotes the counter value of a user within slot t.

The user is then placed in one of the K cells of a K-cell stack depending on the various K possible values. The user could initiate transmission when the counter value is 1 and withholds at $k - 1$ different stages otherwise. All users in a Δ-size window will set the counters to 1and transmit within the first slot of the CRI as soon as it begins. The number of packets in the window will determine whether the first slot will be a collision or non-collision slot. If the window contains one packet then the first slot of the CRI is non-collision and it will last only one slot. On the other hand, if the window contains at least two packets instead of one then the CRI will start with a collision which will be resolved within the duration of the CRI according to the following rules:

- The user transmits in slot t if and only if $r_t = 1$.
- A packet is successfully transmitted in t if and only if $r_t = 1$ and $x_t = NC$.
- The counter values transition in time as follows:

If $x_{t-1} = NC$ and $r_{t-1} = j; j = 2,3, \cdots, k$, then $r_t = j - 1$

If $x_{t-1} = C$ and $r_{t-1} = j; j = 2,3, \cdots, k$, then $r_t = j$

If $x_{t-1} = C$ and $r_{t-1} = 1$, then

$$r_t = \begin{cases} D;\ w.p\dfrac{1}{K} \\ D;\ w.p\dfrac{1}{K} \\ D;\ w.p\dfrac{1}{K} \\ \vdots \\ K;\ w.p\dfrac{1}{K} \end{cases}$$

For any K value, the throughput of the algorithm is 0.43.

The above rules show that a CRI which begins with a collision slot ends with a K consecutive non-collision slots, an event which cannot occur at any other time during the CRI. A user who arrives in the system lacking any knowledge of the channel feedback can still synchronize with the system upon observing the first K-tuple of consecutive non-collision slots. Indeed, the observation of the K consecutive non- collision slots signals the end of a CRI for all users, which either means the end of a CRI that started with a collision or the occurrence of a sequence of K consecutive length-one CRIs. Thus, if a CRI ends with slot t, then the next CRI will involve the packets whose arrivals occurred within the time interval $(t - K + 1 - \Delta\,, t - K + 1)$.

Before participating in a CRI, a packet arrival computes arrival instant updates sequentially; these updates comprise the initialisation rule of the algorithm and dictate the time instant when the packet will first participate in a CRI. The generation of the updates $\{t^k\}$ of the packet is as follows: Let t_0 be the slot within which a packet is generated. Then define t^0 to be equal to t_0. The user will then continuously sense the channel feedback starting with slot t^0. This will continue passively until the user observes the first K-tuple of consecutive NC slots, ending with slot t_1. If $t0\epsilon(\mathrm{t1} - K + 1 - \Delta\,, t1 - K + 1)$ then the user will participate in the CRI starting with the slot $t_1 + 1$.

Otherwise, the user will update the instant of arrival to $t^1 = t^0 + \Delta$ and waits passively until the end of the latter CRI ending with slot t_2. On the other hand, the user will participate in the CRI starting with the slot t_2 if $t1\epsilon(\text{t}2 - K + 1 - \Delta\,, t2 - K + 1)$, otherwise, the user will have to update his arrival instant again by Δ and repeat the process again. In general if $\{t_n\}, n \geq 1$ denotes the sequence of consecutive CRI endings since the first K-tuple of consecutive NC slots, the packet participates in the k^{th} CRI if $t^{k-1}\epsilon(t_k - K + 1 - \Delta, t_k - K + 1)$ and $t^n \notin (t_{n+1} - K + 1 - \Delta, t_n - K + 1)$ for all $n \leq k - 2$.

3.4 Results and Discussion

In this section we present the delay analysis and the Monte Carlo simulation results using MATLAB for both the two cell random access algorithm and the smart two cell random access algorithm. We adopt the limit Poisson user model. Indeed, for a large class of random access algorithm, as the user population increases the stability of the algorithm in the class is determined by its throughput under the Poisson user model. as a worst case scenario, where, subject to this user model, the throughput of a random access algorithm is a lower bound to throughputs induced by any other user model and the algorithm.

Throughput is defined as the maximum Poisson rate λ that the algorithm maintains with finite delays. The throughput and the optimal window results for the 2-cell random algorithm are included in Table 3.1. The analysis leading to these results is included in [7]. The same methodology may be used for the throughput evaluation of any algorithm in the class; the complexity of the induced recursive equations increases, however, as the number of cells in the stack which depicts the collision resolution process of the corresponding algorithm increases.

Table 3.1 Throughput and optimal window

Algorithm	Poisson rate	*Window size*
2-cell algorithm	$\lambda = 0.4297$	$\Delta = 0.4297$

We define the delay D_n experienced by the n^{th} packet as the time difference between its arrival instant and instant when its successful transmission ends. In Figure 3.4 we exhibit the expected delays induced by the 2-cell algorithm, in the absence of smart antennas; thus, in the absence of capture.

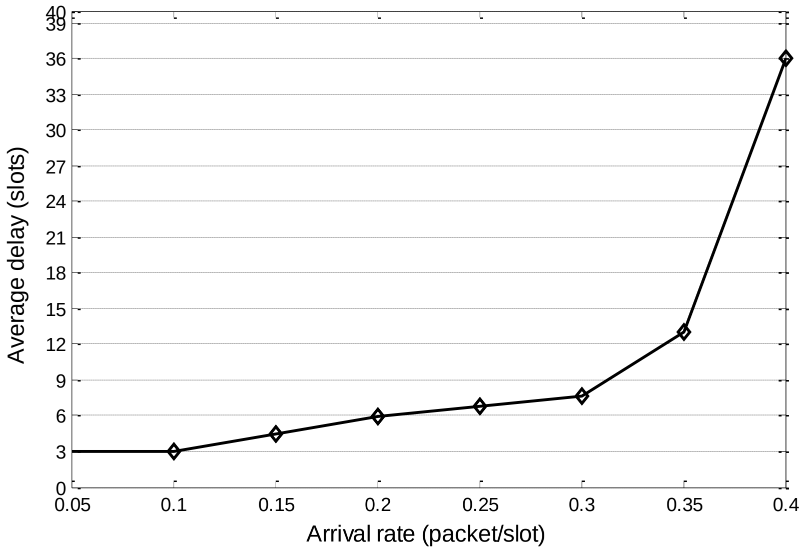

Figure 3.4 Two cell algorithm Expected delays

The two cell algorithm was then simulated with different number of smart antenna elements and plotted with the original two cell algorithm for comparison purposes. Figures 3.5, 3.6 and 3.7 show the expected delays for the smart two cell algorithm for arrival rates being equal to 0.05 to 0.4. We observe that the delays of the *smart* two-cell are not affected as much by the traffic rate and the delays remain low, while the same delays for the regular two-cell are significantly increasing as the rate of the boundary traffic increases. The figures

show that the expected delays of the two-cell algorithm for the rates λ=0.1 to λ=0.3 are relatively low, then after the rate λ=0.3 the expected delay start increasing significantly. On the other hand, the smart two-cell show low delay rates for the rates λ=0.1 to λ=0.3, and also maintain low delay for the rates greater than λ=0.3. Furthermore, we also note that by increasing the number of antenna array elements M the delay performance improved, which shows clearly the effect of employing a smart antenna with more than one antenna elements in increasing the received signal power and thereby improving the delay performance.

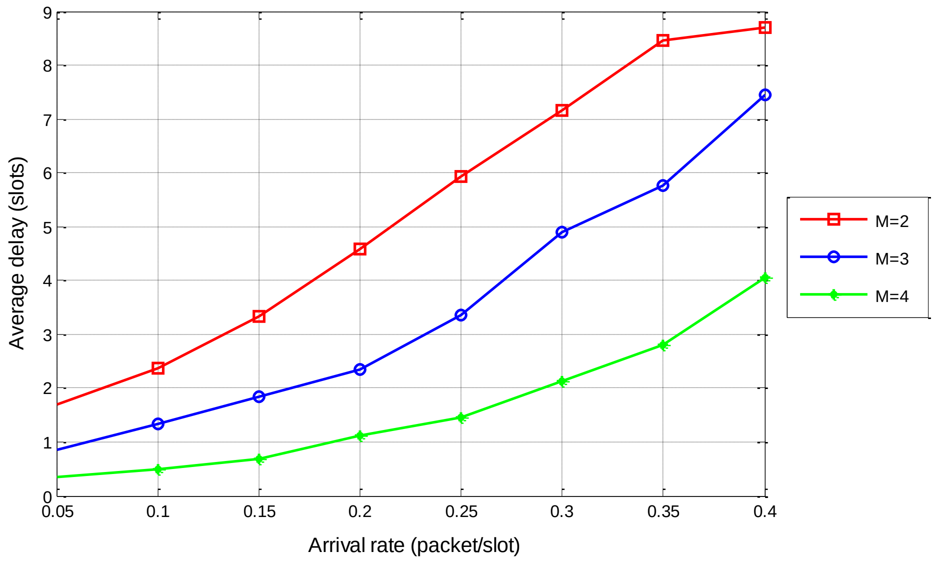

Figure 3.5 Average packet delay performance of the smart two-cell algorithm

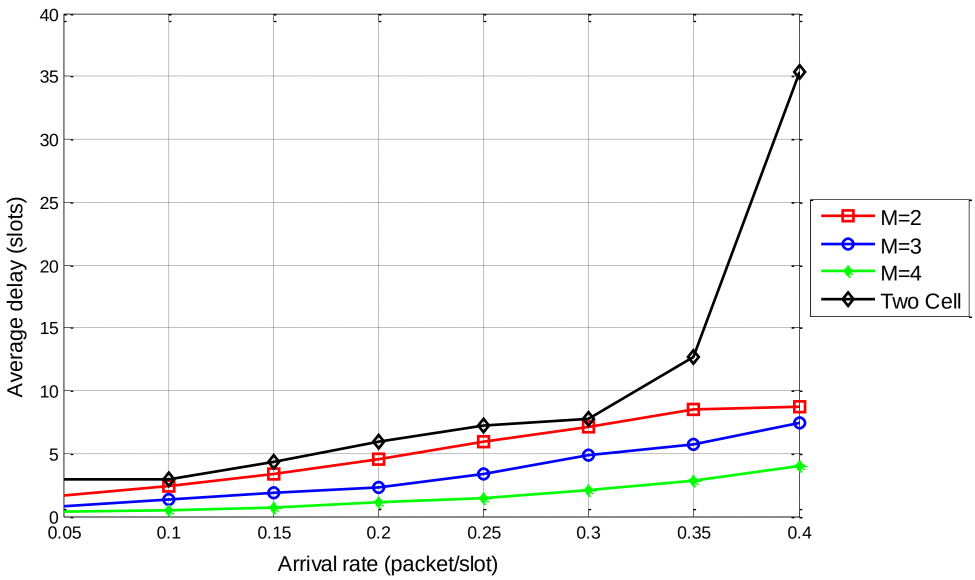

Figure 3.6 Effect of the number of antenna elements M on the two cell algorithm

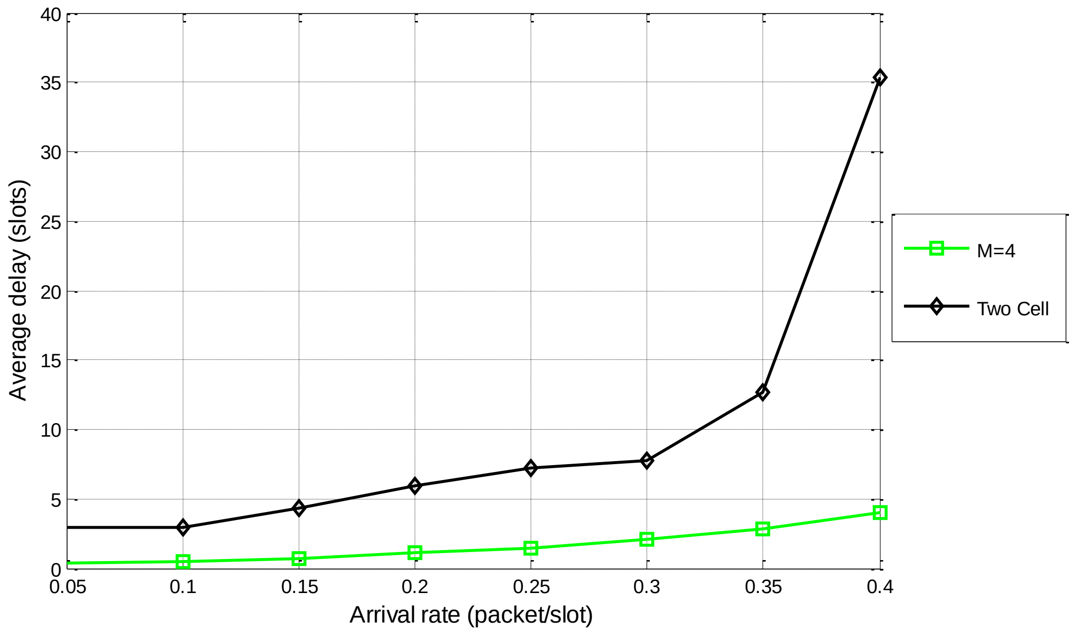

Figure 3.7 Average packet delay performance of the two cell algorithm with the best smart two cell performance $M = 4$

4. Conclusion

4.1 Summary and Conclusions

In this thesis, we considered a mobile random access algorithm for wireless digital networks with smart antennas in a Rayleigh slowly fading multipath channel. The model is a threshold model based on the signal to noise ratio and the protocol is a two-cell random access based protocol for use in ad hoc networks where nodes are equipped with adaptive array smart antennas. The signal received by all antenna elements of a smart antenna is a CDMA signal in the presence of multiple access interference (MAI) and multipath. The smart antenna uses an iterative adaptive LMS algorithm to adjust its weight for better signal reception of the desired signal while minimizing the effect of multipath and interferences. We simulated the two-cell random access algorithm with and without employing smart antennas and exhibited the antenna effect on the algorithm under different design parameters.

We have shown that employing all smart antenna elements significantly improved the performance of the system and reduced the expected delays induced by the two-cell algorithm, especially for higher traffic rates. We have also shown that when we increase the number of array elements from $M = 2$ to $M = 4$, the expected delays decreased. Hence, the simulation results presented showed the performance improvement induced by the proposed communication system containing smart antennas and deploying a smart two-cell algorithm for wideband communication in a Rayleigh slowly fading multipath channel.

4.2 Suggestions for Future Work

From the results obtained it is evident that employing smart antennas, in conjunction with the two-cell random access algorithm, improves communications performance in terms of

delays. The proposed smart antennas deployment may be further explored when other random access algorithms are deployed, such as the three- cell algorithm, for example.

Furthermore, the deployment of the smart two-cell algorithm may be compared to that of the two-cell algorithm with diversity [8], in terms of induced throughput and delays, in the presence of various mobile scenarios.

APPENDIX

In this appendix we present the MATLAB codes used for Monte Carlo simulations of the two-cell random access algorithm without and with smart antenna.

A1. MATLAB Code for the Simulation of the Two Cell Algorithm

```
clear all
clc

lambdaArray = zeros(2,9);
counter = 1;
for  lambda = 0:0.05:0.4
    Tmax=1000;          % maximum time
timeMax = 5;
collision =  zeros (4,10);
    T(1)=random('Exponential',lambda);
    i=1;
         while i < Tmax
            T(i+1)= T(i) + random('Exponential',lambda);
             i=i+1;
         end

      % arrival rate

for i=1:numel(T)
    numberOfCollisionsAtTime = 0
    delay = 0

    for j=1:numel(T)
        if floor(T(j)) == i-1
            numberOfCollisionsAtTime = numberOfCollisionsAtTime + 1;
            collision(1,i) = i-1;
            collision(2,i) = numberOfCollisionsAtTime;
        end
    end


%lambda = ( x ./ times);


if numberOfCollisionsAtTime == 1
    delay = 1;
    collision(3,i) = delay;
elseif numberOfCollisionsAtTime > 1


%cell = zeros(1,2);
  %  transq(i) = x;
    cell(2) = numberOfCollisionsAtTime;
    isResolved = 0;

    while isResolved == 0
        %get the module of cell 2
        mymod = mod(cell(2),2) ;
```

```
        %divide equally into 2 if number of packets are even
        if mymod == 0
            temp = cell(2)/2;
            cell(2) = temp;
            cell(1) = cell(1) + temp;
        %send packet if cell 2 has 1
        elseif cell(2) == 1
            cell(2) = cell(1);
            cell(1) = 0;
        else
        %divide contents of cell 2 and add half to cell 1
            divided = cell(2) - mymod;
            cell(2) = divided/2;
            cell(1) = divided/2 + mymod + cell(1);
        end
         fprintf('[ %d | %d ] \n',cell(1),cell(2));

        delay = delay + 1;

        if timeMax < delay
            isResolved = 1;
            collision(4,i) = 1;
            collision(3,i) = delay;

        elseif cell(1) == 0 && cell(2) == 0
            isResolved = 1;
           collision(3,i) = delay;

            fprintf('\n');
        end

    end
    else

   end
end

k = sum(collision,2);
lambdaArray(1,counter) = lambda;
lambdaArray(2,counter) = k(3,1);
arrivalrate = lambdaArray(1,:);
totaldelay = lambdaArray(2,:)./100;
 totaldelay (:,9)=  totaldelay (:,9)* 2;
counter = counter + 1;
 totaldelay (:,8)=  totaldelay (:,8)* 1.5;
 totaldelay (3:8)=  totaldelay (3:8)./ 2;
end

plot(arrivalrate, totaldelay,  '-d','Color','black');
xlabel(['Arrival rate (packet/slot)']);
ylabel(['Average delay (slots)']);
hold on

  i=i+1;
```

A2. MATLAB Code for the Simulation of the Smart Two Cell Algorithm

```
clear all
clc
R=512; % the correlation length integer
M=4; % number of antenna elements
beta=0.3; %represents the average received power of the
          %interfering signal to the signal power of the
 for  lambda = 0:0.05:0.4
        timeMax=5;
          SNRdb=[-13:2:3]; % for plotting in db
runs=10000;  %number of runs for each SNR value
 lambdaArray = zeros(2,9);
counter = 1;


for i=1:length(SNRdb) % for a range of SNR value for the CUT


       collision =  zeros (4,10);
H1_count=0; % counter of H1
SNR(i)=(10^(SNRdb(i)/10))* 0.5625*R*M;
I= beta*SNR(i);



%T = exprnd(lambda:1000)
   %L = exprnd(M*(1+(M*I)),1,noI);%generate it
    CUT = exprnd(M*(1+(M*SNR(i))),1,1,1000);

L= CUT./ 100;
 % T = L./100

T = sort (L);


for i=1:numel(T)
    numberOfCollisionsAtTime = 0
    delay = 0

    for j=1:numel(T)
        if floor(T(j)) == i-1
            numberOfCollisionsAtTime = numberOfCollisionsAtTime + 1;
            collision(1,i) = i-1;
            collision(2,i) = numberOfCollisionsAtTime;
        end
    end


%lambda = ( x ./ times);


if numberOfCollisionsAtTime == 1
    delay = 1;
    collision(3,i) = delay;
elseif numberOfCollisionsAtTime > 1


%cell = zeros(1,2);
```

```
  %  transq(i) = x;
    cell(2) = numberOfCollisionsAtTime;
    isResolved = 0;

    while isResolved == 0
        %get the module of cell 2
        mymod = mod(cell(2),2) ;
        %divide equally into 2 if number of packets are even
        if mymod == 0
            temp = cell(2)/2;
            cell(2) = temp;
            cell(1) = cell(1) + temp;
        %send packet if cell 2 has 1
        elseif cell(2) == 1
            cell(2) = cell(1);
            cell(1) = 0;
        else
        %divide contents of cell 2 and add half to cell 1
            divided = cell(2) - mymod;
            cell(2) = divided/2;
            cell(1) = divided/2 + mymod + cell(1);
        end
         fprintf('[ %d | %d ] \n',cell(1),cell(2));

        delay = delay + 1;

        if timeMax < delay
            isResolved = 1;
            collision(4,i) = 1;
            collision(3,i) = delay;

        elseif cell(1) == 0 && cell(2) == 0
            isResolved = 1;
           collision(3,i) = delay;

            fprintf('\n');
        end

    end
    else

   end
end

k = sum(collision,2);
lambdaArray(1,counter) = lambda;
lambdaArray(2,counter) = k(3,1);

counter = counter + 1;

end

end

z = [0 0.05 0.1 0.15 0.2 0.25 0.3 0.35 0.4]
arrivalrate = z;
totaldelay = lambdaArray(2,:) ./200%
R= polyval (arrivalrate,totaldelay);
```

```
plot(arrivalrate, totaldelay,  '-*','Color','green');
hold on
xlabel(['Arrival rate (packet/slot)']);
ylabel(['Average delay (slots)']);

  i=i+1;
```

REFERENCES

[1] L. C. Godara, “Applications of Antenna Arrays to Mobile Communications, Part I: Performance Improvement, Feasibility, and System Considerations” , *Proceedings of the IEEE,* vol. 85, No. 7, pp. 1031-1060, July 1997

[2] L. C. Godara, “Applications of Antenna Arrays to Mobile Communications, Part II: Beam-Forming and Direction-of-Arrival Considerations” , *Proceedings of the IEEE,* vol. 85, No. 7, pp. 1195-1245, August 1997

[3] J. Hsu and I. Rubin, “Performance Analysis on Directional Random Access Scheme for Multiple Access Mobile Ad-Hoc Wireless Networks*”, IEEE Military Communications Conference*, MILCOM 2005, vol. 1, pp. 45-51, October 2005.

[4] H. Harkirat, “Smart-802.11 MAC protocol for use with Smart Antenna”, *IEEE international communication conference,* Vol. 6, pp. 3684-3688

[5] W. K. Fung, M. Hamdi, and R. D. M. Murch, "Performance Evaluation of Mobile Radio Slotted ALOHA with Smart Antennas", *IEEE Wireless Communications and Networking Conference*, WCNC 1999, vol. 1, pp. 271 - 275

[6] A. T. Burrell and T. P. Papantoni, “A Class of Limited Sensing Random Access Algorithms with Resistance to Feedback Errors and Effective Delay Control”, *Journal of Communications and Networks,* Vol. 8, No. 1, pp. 21-27, March 2006

[7] A. T. Burrell and T. Papantoni, “Signalling Protocols for Wireless Networks, *3rd International Conference Broadnets*, San Jose, California, October 1-5, 2006.

[8] B. Yucel and H. Delic, “Mobile Radio Window Random-Access Algorithm with Diversity”, *IEEE Transactions on Vehicular Technology*, vol. 49, no. 6, November 2000

[9] I. Stevanovi´c, A. Skrivervik and J. R. Mosig, *Smart Antenna Systems for Mobile Communications*, Final Report, Laboratoire d’Electromagnetisme et d’Acoustique, Ecole Polytechnique Federale de Lausanne, Switzerland, January 2003.

[10] M. Barkat, *Signal Detection and Estimation,* 2nd edition, Artech House, Boston, MA., USA, 2005

[11] K. S. Zigangirov, *Theory of Code Division Multiple Access Communication*, 1st Edition, Wiley-IEEE Press, 2004.

[12] R. Pickholtz, D. L. Schilling, and L. B. Milstein, "Theory of Spread-Spectrum Communications -A Tutorial," *IEEE Transactions on Communications,* vol. 30, pp. 855-884, 1982.

[13] D. Campana and P. Quinn, "Spread-spectrum communications," *IEEE Potentials*, vol. 12, pp. 13-16, 1993.

[14] D. Prabakaran, “Spread-Spectrum Technology and its Application,” *Electronics for you*, pp. 104-114, December 2005

[15] I. J. Meel, "Spread Spectrum (SS) introduction," De Nayer Institut, Belgium, 1999.

[16] M. K. Simon, J. K. Omura, R. A. Scholtz, and B. K. Levitt, *Spread Spectrum Communications Handbook*, McGraw-Hill, 2002.

[17] R. A. Monzingo, R. L. Haupt, and T. W. Miller, *Introduction to Adaptive Arrays*, Scitech Publishing Inc., Raleigh, NC., USA, 2011.

[18] A. Sofwan and M. Barkat, "PN code acquisition Using Smart antennas and adaptive thresholding trimmed-mean CFAR processing for CDMA communication,"*Spring World Congress on Engineering and Technology* (SCET2012), Xi'an, China, 2012.

[19] R. R. Rick and L. B. Milstein, “Optimal decision strategies for acquisition of spread spectrum signals in frequency selective fading channels”, IEEE Transactions on Communications, vol. 46, No. 5, pp. 1613-1628, Nov. 2001.

[20] F. Gross, *Smart Antennas for Wireless Communications with Matlab*, McGraw-Hill, New York, USA, 2005.

[21] M. schwartz, *Telecommunication Networks Protocols, Modelling and Analysis*, Addison Wesley, UK. 1987.

[22] C. E. Shannon, “Two-Way Communication Channels”, *Proceedings of the fourth Berkeley Symposium on Probability and Statistics*, pp. 611-644, Berkeley, CA, 1961

[23] A. T. Burrell and T. P. Papantoni-Kazakos, "Random Access Algorithms in Packet Networks—A Review of Three Research Decades," *International Journal of Communications, Network and System Sciences*, Vol. 5 No. 10, 2012, pp. 691-707.

[24] M. Zorzi, “Mobile radio slotted ALOHA with capture and diversity,” *Wireless Networks*, vol. 1, pp. 227–239, May 1995.

[25] M. Zorzi, “Mobile radio slotted ALOHA with capture, diversity and retransmission control in the presence of shadowing,” *Wireless Networks*, vol. 4, pp. 379–388, August 1998.

[26] M. Zorzi and R. Rao, “Capture and retransmission control in mobile radio,” *IEEE Journal on Selected Areas in Communication*, vol. 12, pp. 1289–1298, Oct. 1994.